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NATIONAL RESEARCH COUNCIL

COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS

2101 Constitution Avenue Washington, D.C. 20418

AERONAUTICS AND SPACE
ENGINEERING BOARD

November 29, 1995

Mr. Wilbur C. Trafton
Deputy Associate Administrator
for Space Flight (Space Station)
NASA Headquarters
HQ7A40
Washington, DC 20546-0001

Dear Mr. Trafton:

On behalf of the National Research Council's (NRC's) Committee on Space Station, I am pleased to provide you with the committee's findings and recommendations on the following International Space Station (ISS) issues: (1) testing and verification, (2) contingency planning, (3) crew time utilization, and (4) power. The objective of this document is to summarize the committee's findings and to identify issues in the above topic areas that would benefit from more in-depth study rather than to provide comprehensive, in-depth analyses and specific recommendations, which were beyond the scope of the committee's activities.

The Committee on Space Station was established by the NRC in 1991, at the request of the National Aeronautics and Space Administration (NASA) Administrator, to study the Space Station design and program plan. Since February 1995, the current committee has been receiving briefings from both NASA and contractor personnel on the four issues listed above at full committee meetings and at subcommittee site visits. In many instances, the committee members followed up with additional questions to be addressed in writing. In all cases, NASA was open and responsive to the committee's inquiries and requests. The information provided was essential in allowing the committee to examine the issues and formulate its independent opinion. The committee recognizes the extremely tight ISS schedule and the heavy workloads of ISS personnel. We would like to express our appreciation through your office to all participating NASA and contractor personnel.

TESTING AND VERIFICATION

ISS represents the largest, most complex testing and verification task in the history of space-vehicle development. Current plans call for 19 separate spacecraft, developed by an international partnership, that ultimately will be interconnected in space to provide a platform supporting research and technology development in areas critical to the future exploration of the Universe. The program is so large and so complex that traditional methods of spacecraft testing and verification are inadequate to complete the task. The classical approach of complete hardware and software verification and validation prior to launch is both cost prohibitive and logistically infeasible.

To respond to these unique circumstances, NASA plans to utilize multitiered testing, compatible with the distributed, multistage ISS design, under control of the ISS prime contractor. The program will rely heavily on the ISS Independent Assessment Office at the Johnson Space Center (JSC), which reports to the NASA Associate Administrator for Safety and Mission Assurance, to maintain audit oversight of ISS testing.

Issues Addressed

The committee concentrated its efforts during the past year on reviewing current Space Station Program Office test planning and management. Specifically, the committee examined (1) the organizations responsible for the development and maintenance of the ISS master test plan within NASA and the Space Station Program Office; (2) the testing goals, objectives, and plans; (3) the testing hierarchy and the roles and responsibilities of NASA, the contractors, and the subcontractors; and (4) the role of the Russians in testing and verification and the planned use of Russian test and integration experience.

Findings and Recommendations

The committee's findings and recommendations on testing and verification are listed below.

1. A detailed briefing on ISS testing was presented to the committee on July 24, 1995, by the manager of the NASA Vehicle Test and Verification Team. The briefing covered the testing methodologies being used by the Space Station Program Office to perform ISS test and verification. The committee believes that the team appears to have a good understanding of product group and subsystem testing issues. However, end-to-end integrated testing of launch packages and of the evolving orbital configuration plans is not as clearly defined.

2. Overall test management is not optimal considering the criticality of this function and the degree of change from conventional approaches. The Vehicle Test and Verification Team reports to the Vehicle Analysis and Integration Team, which in turn reports to the Vehicle Manager's Office, which is two levels below the ISS Program Director. No direct line of responsibility from the Vehicle Test and Verification Team to the Program Director was identified by NASA. An Independent Assessment Panel chartered to review ISS activities and reporting to the Safety and Mission Assurance Associate

Administrator is partially responsive to the committee's concern that there be an independent test organization.

The roles and responsibilities of both NASA and contractor personnel in the test program must be clearly defined (preferably with NASA staff responsible for test management, review, and approval of results and the contractor responsible for detailed test-plan development and test execution).

The committee recommends that the group responsible for ISS testing and evaluation be elevated in the management structure to at least equal status with the other integrated product teams, with an independent reporting path to the ISS Program Director. Staff who are responsible for what is, in effect, oversight of the work of other product teams should not report administratively to any of those teams.

3. Adjusting to the change in ISS test strategies from the classical "complete testing on the ground prior to launch" strategy is difficult. The current strategy is to provide the maximum amount of functional testing and verification for every area possible and/or critical on the ground and in as close to environment conditions as possible consistent with cost, schedule, and physical and programmatic constraints. Although the ISS has been designed to be assembled on orbit, a complementary preoperational, on-orbit test program, augmenting the level of testing that can be accomplished on the ground, does not appear to exist. On-orbit testing in areas where ground testing is not feasible can be a critical adjunct to prelaunch testing.

 Decisions need to be made as soon as feasible regarding test strategies and plans for integrated testing as the various launch packages evolve into the completed ISS. The level of testing on the ground and on orbit needs to be defined, and the role of the crew during assembly should be specified. Decisions on the use of simulation, emulation, and other methodologies to augment hands-on flight hardware testing should be made.

 Maximum use should be made of state-of-the-art knowledge and experience in testing large, complex systems in both the defense and commercial arenas and the experience gained in testing unmanned NASA, military, and commercial spacecraft. Information could be gained from the U.S. Air Force, the Department of Defense, and from implementers of large commercial communications systems.

4. The Russian entities involved in the development of ISS hardware and systems do not appear to be integrated into the overall ISS test and verification program.

Test and evaluation activities of all the partners should be integrated at their respective contractor/subcontractor level to minimize the disruption to the assembly schedule and to permit the creation of work-around contingency plans.

Test management could be further augmented by the formation of an ISS test-planning working group consisting of representatives of all ISS partners. This group would be responsible for oversight and concurrence on the ISS Master Test Plan, with final approval of the plan required from the ISS Program Director. The plan should be updated annually until the assembly-complete milestone is achieved.

5. **Although the committee did not address integrated hardware/software testing in detail, it acknowledges that software testing is invariably more difficult than expected and believes that the ISS program would greatly benefit from an in-depth review of all testing and verification issues, including software.**

CONTINGENCY PLANNING

Current plans require 44 deployment and utilization missions as well as 29 additional logistics flights with both people and materiel during 1997–2002. The sheer magnitude of this number of space launches, in light of the historical reliability of worldwide space transportation systems, dictates the development of a comprehensive assembly contingency plan that can be invoked in the event of the loss of any ISS payload or the unavailability of a particular launch vehicle. Moreover, the original and unique aspects of many station elements could lead to unanticipated technical delays in preparing some payloads for launch.

Contingency plans must, therefore, provide ISS program managers with the most efficient and cost-effective recovery options following significant disruptions in the assembly schedule. Scenarios that may cause such disruptions include (1) the loss of a payload during launch, (2) the loss of a payload during orbital rendezvous (expendable-launch-vehicle missions), (3) an inability to dock ISS elements, (4) a hiatus in unmanned space transportation systems operations due to a launch failure (ISS or non-ISS related) or infrastructure deficiencies, (5) the need to requalify man-rated spacecraft or launch vehicles following an accident, (6) inability to integrate a newly-arrived module with the existing ISS systems, and (7) a major failure of an ISS element after integration into the station. The last possibility was not a principal subject of the committee's investigation.

Issues Addressed

Contingency planning for ISS may involve a number of factors. These include (1) the procurement of long-lead-time spares or raw materials, (2) the adoption of element designs that would facilitate the use of multiple space-transportation systems, (3) the improvement of infrastructures susceptible to major disruptions due to single-point failures, (4) the design of alternative systems or launch vehicles to be used in the event of the withdrawal of an international partner from the program, and (5) alternative assembly configurations (temporary or permanent) and ISS operations, or simple suspension of assembly flights until the disruption can be rectified. In the event that a payload is returned to Earth, issues associated with requalification of the unit(s) prior to reflight may also fall under the category of contingency planning. Of primary concern is the maintenance, in a manned or unmanned mode, of the station elements already on orbit should further deployments be delayed.

While a detailed fault-tree analysis and recovery plan for every possible eventuality during assembly is not feasible, at a minimum, a first-order examination of the most likely occurrences and of those that would create the longest delays in achieving the ISS Phase 2 and Phase 3 milestones needs to be undertaken. Examples of such occurrences include:

- nonavailability of the FGB (Russian Functional Cargo Block module) or Service Module;
- extensive delay or loss of other ISS flight packages;
- temporary suspension of Space Shuttle, Soyuz, Proton, or Zenit launch operations;
- nonavailability of the Progress-M/M2 (Russian unmanned resupply spacecraft);
- loss of a Shuttle orbiter (on an ISS or other mission);
- failure of a Soyuz-TM (Russian man-rated spacecraft) Assured Crew Return Vehicle (ACRV) during return to Earth; and
- inability to perform a critical extra vehicular activity (EVA) task.

Findings and Recommendations

The committee's findings and recommendations on ISS contingency planning are listed below.

1. Overall, NASA contingency-planning activities for ISS appear to be well organized and staffed by competent personnel.

2. System-level designs for U.S.-produced alternatives to the Russian FGB, the Service Module, and the Progress-M/M2 have been created. Launches of these options have been devised that use the U.S. expendable launch vehicles or the Space Shuttle. Also, techniques for exploiting Space Shuttle reserves to reduce the frequency of independent propellant resupply missions (Progress-M/M2) have been identified.

3. The Space Station Program Office has established contingency planning teams to investigate responses to non-nominal assembly operations. Flight-by-flight

assessments are scheduled for completion by late 1995, and priority recommendations for providing adequate spares for critical components and other alternatives are due by 1996.

All contingency planning activities should be integrated and given high-level management visibility.

For the early flights, where there is little flexibility in the order of assembly, strong consideration should be given to providing spares for critical hardware.

4. Alternatives to the Russian-supplied ACRV are not planned until after Phase 3 has been completed. Preliminary designs should be available by 1998.

   Design studies for alternatives to Progress-M/M2 and Soyuz-TM should be continued and expanded to meet acquisition Phase A/B criteria. These systems also may be considered to support ISS logistics requirements in the post-2002 period.

5. Current assembly plans provide significant orbital longevity for assembled elements in the event of resupply interruptions. Reduced station operations can be maintained for as long as 24 months in some cases.

   The international partners should expand the breadth and fidelity of contingency planning during planned Phase 2 and Phase 3 operations. Greater emphasis should be placed on devising innovative assembly configurations to minimize ISS construction delays if a payload is lost or considerably postponed. Launch and on-orbit storage should be considered for appropriate elements following an assembly schedule disruption.

6. NASA considers out-of-sequence assembly options to be severely limited during 1997–1998. As ISS evolves, flexibility in launch and assembly operations will grow. Current contingency plans attempt to maximize utilization potential during unscheduled assembly delays, although some utilization activities may be curtailed in favor of others due to electrical power or other resource constraints.

   EVA contingency planning emphasizes increasing crew capabilities and flexibility. EVA margins (i.e., untasked EVA time), U.S.-Russian EVA cross-training, and well-equipped EVA toolkits will increase the probability of accomplishing EVA objectives.

   EVA contingency planning should include alternatives for instances when EVA objectives cannot be met with existing resources, (e.g., when extended

hours or additional crew members are necessary). Although not specifically addressed by the committee, contingency plans also should be made for planned scientific experiments in the event of a change to the assembly schedule or sequence and for crew safety during EVAs.

CREW TIME UTILIZATION

Good planning for utilization of the ISS crew is essential to the long-term success of ISS as a research platform. In presentations to the committee, NASA indicated that a three-person crew will be responsible for ISS construction and for conducting experiments during the early phases of assembly. When the ISS assembly is complete, an international six-person crew will be responsible for operating and maintaining ISS and for conducting experiments and some research activities.

Issues Addressed

Operating and maintaining any large research facility with only six people requires careful management of staff time under normal circumstances. When the facility is located in space and the crew is composed of individuals from various countries and disciplines, many of whom speak different native languages, operations will be more complex; therefore, careful planning is essential. In order to maximize the crew's time for research when assembly is complete, system upgrades and automated operations will become very important. Otherwise, as ISS ages, maintenance and operations activities are likely to become more and more time consuming. Because crew time is a critical resource that is essential to the long-term success of the ISS program, the committee examined (1) the roles and responsibilities of the organization within NASA responsible for crew time planning; (2) the plans for crew composition in terms of nationality and skills; (3) titles, roles, and responsibilities of the crew members; (4) provisions planned to ensure the emotional well-being of the crew members; and (5) NASA's plans for future automation and systems upgrades.

The committee concentrated on crew time utilization at the assembly-complete phase, recognizing that the number of launches, the complexity of tasks to be performed, and the EVA schedule will limit the research activities of the three-person crew that will be present during the assembly phase.

The committee acknowledges that its work on this issue has been preliminary. Clearly much more needs to be done. There needs to be an understanding of how this international research laboratory will be staffed, how/when the work is to be done, and how work priorities will be established. Further, the basic breakdown in functions such as maintenance, housekeeping, and research for a baseline crew needs to be understood. The Mercury/Gemini/Apollo/Shuttle models of crew utilization are inappropriate, and the

Skylab model is questionable. While the Russian experience will be extremely useful, emphasis on increased productivity will be important.

Findings and Recommendations

The committee's findings and recommendations on crew time utilization are listed below.

1. There appears to be one organization at Johnson Space Center (i.e., the Space Station Program Office) providing the operation and utilization concepts for ISS. There are no apparent organizational interfaces between the Space Station Program Office and the Mission Operations Directorate. In addition, there does not appear to be an ISS office within the Mission Operations Directorate. The connection with Marshall Space Flight Center and the other Centers and organizations that are providing hardware and experiments also is unclear.

2. Current crew-utilization planning for the operations phase of ISS appears to be centered in the Space Station Program Office and the Astronaut Office at JSC, with little input from the scientific user community. The Space Station Program Office already has a monumental job to get ISS assembled within budget and on schedule, and to coordinate with the Astronaut Office to plan crew activities during ISS assembly.

   Responsibility for crew-utilization planning after assembly is complete needs to be assigned now to some organization consisting of the primary users of ISS, the Office of Life and Microgravity Sciences and Applications, and the Office of Space Access and Technology. The designated crew office also should be represented.

3. The Space Shuttle crew titles currently are being applied (probably by default) to ISS. Although some carryover from the Space Shuttle era is certainly appropriate, there is no clear reflection of the international aspect of ISS or the differences in crew requirements between the assembly and fully operational phases of ISS.

   Since Space Shuttle flights will continue during ISS assembly and operation, a separate vernacular of crew definition for ISS would be helpful.

4. Crew composition should be a function of ISS phase (i.e., assembly or operation), participating countries, and scheduled payload operations. It is unclear to the committee to what extent any of the above factors are being considered. If such decisions are being made solely by Missions Operations Directorate, then the requirements of the scientific and international

communities may be neglected. The timeframe is optimum now, with all of the partners onboard, to begin real analysis and planning for crew composition.

The crew should be an integrated whole for each phase and increment, not segregated by nationality.

Guidelines should be developed that relate crew composition and skill mix to the experiment disciplines, with the overlying constraint of international participation.

For missions focusing on specific disciplines, consideration should be given to using specialized crew members, similar to the payload specialists on Space Shuttle missions.

5. There does not appear to be any detailed planning for crew time allotment on ISS, which may lead to ISS operation without adequate guidelines. The Space Shuttle scheduling procedures have some applicability, but they become obsolete when long-duration on-orbit missions are considered.

   A set of crew-time allotment guidelines, similar to those for Space Shuttle, should be developed in cooperation with the international partners, using the knowledge gained from the Russian partnership. These guidelines would consider launch day, the start-up period at Space Station, a typical on-orbit day, and crew changeover prior to leaving ISS. Considerations for crew time allotment based upon crew definition also should be included in the guidelines. For example, the payload specialist-type crew member would be allotted more time for payload experiment operation, and other types of crew members might be allotted more time for payload maintenance. Further, since crew members will be conducting hands-on research, the needed time to analyze data on-orbit as well as to develop and maintain technical skills by reading or working with equipment should be considered.

6. The Concept of Operations and Utilization document states that "All crew members will be available to participate in human research." Without further definition of "crew" and "human research," this opens up considerable speculation as to the use of the crew. A principal goal of ISS is to understand human long-duration space reactions and to develop countermeasures. Crew assignments and training must recognize the possible dual-usage of crew for the vital human life-science experiments.

   All crew members, regardless of title, discipline, or nationality, should be available to participate as test subjects for ground-based preflight and postflight tests, as well as inflight tests, aboard ISS.

Provision should be made for increasing onboard stays to evaluate deconditioning and countermeasure effectiveness for potential Mars missions.

Constraints should be developed to govern the scheduling of crew members for biomedical activities to ensure that someone is available to handle emergencies and that the other experiments are not adversely impacted by either invasive or provocative tests. These constraints also should reflect the requirements of all of the scientific disciplines as well as those of the international community.

7. Although it is generally stated that ISS will be simple, robust, and automated where necessary, there are no apparent guidelines for either the experimental or operation and control hardware on ISS. In addition, considering that it is difficult to effect any changes once a piece of equipment is designated as flight-qualified hardware, action should be taken now to ensure that hardware being placed on ISS can be upgraded and automated if possible. The long-duration operation of ISS and the extensive time period during which it is being assembled necessitates that hardware and control systems will need to be upgraded.

   The Space Station Program Office should assign responsibility for developing specific guidelines for incorporating automation into the experimental and operational and control hardware on ISS.

8. To date, only the position of Commander has been defined. Approval of the use of crew resources is required from the ISS Program Manager. Preliminary weekly schedules provided by NASA, appear to be oriented to the needs of the ground support team; that is, the crew works a rigidly-scheduled, 8-hour day, with specific times set aside for sleep, meals, personal hygiene, planning and coordination, and countermeasures, with "housekeeping" scheduled for Saturday mornings, and Sundays designated as days off.

   Since it is a critical resource, crew time should not be driven by the schedule of the ground support team, and NASA should determine the best schedule to optimize the crew's time.

9. Training is defined as "mission oriented" (as designed for Space Shuttle missions), implying a well-defined, short-term mission in space to perform some specific task, such as "repair the Hubble Space Telescope." NASA astronauts are developing standards for crew-experiment interaction, but only relatively limited onboard telescience support is planned. Currently, there are no standards for experiment operation, level of crew support, and degree of automation to be provided by the experimenter. Uplink television capability in the U.S. portion of ISS, which could be of major assistance to the crew in

demonstrating hands-on problem solving as well as in providing an important component of crew emotional well-being, will not be available. However, uplink capability will be available on the Russian portion of the ISS.

Training should include both the preflight experiment training with the investigators and inflight refresher training.

The use of telescience to alleviate the pressure on crew time should be maximized. To enable off-station specialists to assist with operations, two-way, digital-video networking should be conveniently available at locations on Earth, inside ISS, and outside ISS during EVA.

The Space Station Program Office should assign responsibility for developing guidelines on how to incorporate automation in ISS research experiments and operations.

NASA should include the research community in determining how to increase the level of automation (telescience, telepresence) in all research packages. This would enhance the role of the experimenter on the ground, reserving the critical resource of onboard astronaut/mission specialists for problem solving and other critical events where only hands-on human intervention will suffice.

10. Crew utilization planning should build on the body of experience represented by the Skylab missions, by the Russian space stations, and possibly by long-duration naval submarine missions.

    NASA needs to begin a major effort in crew-utilization planning, with strong participation from the scientific user community. This study, leading to a long-term plan for station operations in the postassembly era, may become the responsibility of NASA Headquarters. The Space Station Program Office should be involved in the study only in a support capacity, because their concentration must be focused on building ISS. The study needs to proceed rapidly because the resolution of certain issues (video uplink, automation, technology insertion, etc.) may impact certain areas of the ISS final design.

POWER

The ISS power system includes the integrated power generation, storage, control, and distribution equipment and facilities needed to produce electrical power and provide it at user interfaces. The system will be jointly built and operated by the United States and Russia. The on-orbit U.S. portion includes solar arrays, beta gimbals, energy-storage subassembly, power management and distribution orbital replacement units, cabling, and the alpha gimbal. The standard, conditioned utilization voltage on the U.S. portion will be 120 volts dc, negatively grounded, and the standard voltage on the Russian portion will be 28 volts dc, resistively center-point grounded. Further complicating the power-system life-cycle design and operation are interactions with radiation, debris, micrometeoroids, plasma, atomic oxygen, and outgasses that are unique to the ISS operating environment.

Issues Addressed by the Committee

Because power is essential in supporting human life in space, as well as the operational and maintenance aspects of ISS, the committee examined the major components of the electrical power system in the context of design, operation, and interactions with outgasses produced during EVAs and Shuttle dockings/undockings. Since insulation materials are used extensively on ISS and are essential in maintaining proper power-system operation, the committee carefully examined the interactions between EVA and Shuttle outgasses, operating voltage and frequency, and temperature, as well as their effect on the generation of partial and glow discharges. The committee's main concern became focused on the premature degradation and aging of insulation materials.

The Space Shuttle and EVA outgasses can pressurize electrical power equipment, which in turn can initiate the generation of partial discharges or sustained glow discharges. A partial discharge is a transfer of electrons (i.e., small current) between surfaces that can lead to the destruction of a surface, such as the solar-array coating. A glow discharge results when a high-voltage surface is charged relative to its environment, resulting in a localized temperature increase. This, in turn, can lead to the initiation of partial discharges and local degradation of insulating materials. Insulation materials shrink with age and temperature and degrade much faster when exposed to partial and glow discharges.

Findings and Recommendations

The committee's findings and recommendations on ISS power are listed below.

1. The electrical power system design is sound. In the current plans, the power levels for ISS operations and science meet the requirements for the assembly complete configuration. Although there are some technologies and capabilities (as noted below) that could be inserted to reduce maintenance and increase life-cycle efficiency, the committee identified no major design issues that would prevent the system from working as planned. The relevant NASA and contractor staff appear to be knowledgeable, responsive, and competent.

2. In some areas, such as battery technology, NASA is investigating use of Russian technology for future upgrades. For example, NASA Lewis Research Center is conducting tests on Russian nickel-cadmium batteries, which have been shown to have a longer life and better operating characteristics than U.S. nickel-cadmium batteries. The data should be available in 1996.

3. The lifetime of high-voltage solar arrays has been shown to be a function of exposure to atomic oxygen erosion, electromagnetic and particle radiation, debris and micrometeroid damage, and outgassing. Steps are being taken to produce a homogeneous layer of silicon oxide (SiOx) on the photovoltaic arrays. This would reduce the possibility of SiOx penetration and eventual defect formation and would inhibit partial discharges, flashover, and arcing. The first SiOx solar cells will be flown on MIR in the next few months, and the test results should be available within 6 months. If the SiOx coating operates effectively over the 20-year predicted design life, the solar array and its generated power should be very stable.

   To increase solar-array–cycle lifetime, new technologies, such as metallization and self-clearing insulation topologies, could be considered in the next generation systems. Since solar-array voltages are modest, impacts would result in safe electrochemical clearing, hence returning the solar array to full-voltage potential. Further research into the graceful aging techniques that are being developed in modern electronics may well enable significantly enhanced life-cycle reliabilities and available life of solar arrays in the space environment.

4. Partial discharges may do little or no damage initially. However, as the ISS solar array ages, these discharges, when combined with the negative voltage generated by the plasma contactor used to maintain a neutral charge on the solar array, may induce surface flashovers across the solar array, and lead to the deterioration of the system. The use of the plasma contactor may be a plus for ISS charging but a negative for solar array bulk discharges and enhanced degradation. The contactor may add a greater overall potential between the plasma and solar array, making the solar-array voltage to the plasma greater than 200 volts. The greater the voltage between the plasma and solar array, the higher the probability for arcing on the solar array.

5. In the battery charger, the switched-mode power conditioning system utilizes a dc–dc converter unit with frequencies and peak voltage potentially capable of initiating partial discharge when either a Space Shuttle is docking or undocking or an astronaut or cosmonaut gets too close to a converter. Evaluation of Space Shuttle and EVA suit outgassing as a function of distance should provide guidelines for Space Shuttle and EVA operations in the proximity of both power conversion equipment and insulating materials to prevent a reduction in both component and insulation lifetime.

6. Extensive use of line-to-line EMI (electromagnetic interference) filters and/or attenuators may prevent the detection of partial discharges within potential fault intolerant modules. Very small quantities of partial discharge or flashover do not generate either large transients or current increases. These

types of discharges can only be detected by specially designed detection instruments for high-frequency applications. Having partial discharges and small intermittent flashover will not instantly age modules. Several days of accumulated discharge time are required for failure.

7. The EMI/EMC (electromagnetic coupling) specification does not include verification testing at various pressures and at specific frequency spectra that produce glow discharges. However, load surges and transients will be included.

8. In regard to degradation of insulation materials, it was found that NASA has written an excellent set of assembly-in-space guidelines based on experiences gained during the Skylab, Space Shuttle, and Hubble Space Telescope repair missions. Long wire and cable lengths will be clamped or "stayed" in a position such that shrinkage will be confined to very short lengths of wire and cables. For many components, both solid and braided shielding and glass mat coatings will be used to reduce the exposure of insulating materials to sunlight and outgassing. This also will improve aging. For some ISS components, however, Kapton (polyimide), whose resistivity decreases dramatically (over two orders of magnitude) with exposure to ozone and ultraviolet light, will be either the primary or only insulation. It was unclear to the committee that this life-limiting characteristic had been thoroughly considered.

9. NASA is planning to minimize insulation aging resulting from tension-induced cold flow by using individually shielded conductors, multilayered insulation systems, and strict enforcement of clamping guidelines.

10. There are a limited number of generally modest-scale experiments, detection devices, and program modifications that could be implemented after assembly is complete to assure proper, complete reliability and maintainability of all critical hardware modules. In addition, such experiments have the potential for significant enhancement of operational effectiveness of ISS. There may be opportunities to undertake several such investigations on the Space Shuttle or in smaller-scale experiments.

    NASA should plan to conduct experiments that could result in an enhancement of the operational effectiveness, reliability, maintainability, and lifetime of the ISS power system consistent with the above findings.

Other Observations

The May 6, 1993, letter report of the committee recommended enhanced attention to the subject of technology research and development as a mission of the ISS. Response to this recommendation was reviewed, and the committee was pleased with the response of

NASA. Considerable progress has been made, and the results from this important area of research will be one of the ISS's major contributions.

This report provides specific observations and identifies areas that would benefit from additional examination. The scope of the committee's activities did not allow in-depth analyses in the broad areas chosen for review.

The ISS is being developed based upon available and existing technology to the degree feasible. Clearly this is necessary to provide stability to the program and to assure that cost and schedule budgets are maintained. Conversely, many of the technologies critical to the ISS are changing at a rapid pace. Additionally, the ISS is a space facility that will have many years, and probably decades, of useful and productive life. Special attention needs to be paid to the conflicting objectives of establishing initial operations on schedule versus keeping the ISS technologically current. **A technology evolution plan is needed, as is a policy to ensure that current decisions do not unintentionally eliminate opportunities to incorporate new technology in the future.**

The committee has been provided with an overview of many aspects of the ISS. We have chosen to comment in this letter on a few specific areas that are critical to the success of the program. In our meetings with NASA and contractor managers, we had the opportunity to discuss a broad array of topics. We hope this dialogue and the questions raised by the committee were helpful in enhancing the ISS. The committee's main objective has been identifying areas requiring attention and improvement; however, our overall reaction is that the ISS program has made enormous progress and is on course. People with whom we interacted during our review were competent, confident, and generally excited about the program—these are important ingredients to success. We appreciate the opportunity to have been a part of this extraordinary effort and wish you enormous success.

Sincerely,

Tom Young

A. Thomas Young, Chair
Committee on the Space Station

Attachment:
Statement of Task
Abbreviated Member Biographies

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National Research Council
Commission on Engineering and Technical Systems
Aeronautics and Space Engineering Board

Committee on Space Station

Statement of Task

The Committee will review the design and program plan of the U.S. Space Station and identify engineering issues that would benefit from in-depth analysis. The Committee may recommend workshops or in-depth studies on specific issues of concern. The Committee will also accept suggestions from NASA for specific studies. The Committee may establish panels of experts, from within the Committee, from other NRC units, and from the aerospace community at large, to conduct these separate efforts. Panels will report to the complete committee as defined by their individual charters, and the Committee will provide written findings and recommendations as appropriate.

The Committee will meet approximately four times each year to receive briefings from NASA and the space station user community on the status of the program. The Committee will prepare position papers and letter reports as appropriate, on issues that are deemed to be of general interest.

The Committee's findings and recommendations will be presented as reports to the NASA Associate Administrator for Space Flight, the NASA Administrator, relevant Congressional committees, and other concerned parties. These reports and position papers will be subject to National Research Council report review procedures prior to release.

ABBREVIATED BIOGRAPHIES

A. Thomas Young is a member of the National Academy of Engineering and recently retired as the President and Chief Operating Officer of Martin Marietta Corporation, a position he held since 1990. Mr. Young joined Martin Marietta in 1982 as Vice President of Aerospace Research and Engineering. Prior to his positions at Martin Marietta, he was Director of NASA's Goddard Space Flight Center from 1980 to 1982, and held other responsible positions with NASA. Mr. Young has received numerous honors and awards including NASA's highest award, the Distinguished Service Medal, for his role in the Viking Program. Mr. Young received a bachelor of aeronautical engineering degree and a bachelor of mechanical engineering degree from the University of Virginia in 1961 and master of management degree from the Massachusetts Institute of Technology in 1972.

Jack Blumenthal is Assistant Director of the Center for Automotive Technology at TRW. In more than 30 years at TRW, Dr. Blumenthal has held a number of responsible positions in the areas of chemical engineering, chemistry, materials science and energy conversion, including chief engineer in the Applied Technology Division of the Space Technology Group. He earned his Ph.D. at the University of California at Los Angeles where he did research in catalytic afterburners for automotive applications. From 1986 to 1989, he was a member of the NRC Panel on Technical Evaluation of NASA's Proposed Redesign of the Space Shuttle Solid Rocket Booster.

Barbara Corn is a technical consultant with over twenty years experience in the review and evaluation of major government programs. Her consulting firm specializes in programming languages, hardware and software architectures, space systems survivability, satellite autonomy, fault tolerance, and the application of expert systems. Projects undertaken by her firm, since Ms. Corn left the Aerospace Corporation in 1983, have included analyses in support of the Defense Meteorological Satellite Program, the hardware and software information systems for the Strategic Defense Initiative, and the Space Station Freedom data and information systems.

Edward Crawley, a Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology, is a specialist in the design and dynamics of space structures, and Director of MIT's Space Systems Laboratory. Dr. Crawley was awarded his Ph.D. from MIT in 1980. Dr. Crawley was a member of The President's Advisory Committee on the Redesign of the Space Station (in 1993) and the NASA Space Station Advisory Committee. He also served as a technical advisor to the 1987 NRC Committee on Space Station. He has been active in international cooperation in space programs and in 1990 was awarded the Gold Medal award of the Gagarin Flight training center for contributions to Soviet-American space efforts.

John Fabian is President and CEO of Analytical Services Inc. and a past president of the Association of Space Explorers. Dr. Fabian is a former astronaut who flew as a Mission Specialist on two Space Shuttle Missions, STS-7 and STS-51-G, in 1983 and 1985 respectively. He is also a former associate professor of aeronautics at the Air Force Academy and was a member of the investigative staff (responsible for Mission Planning and Operations) for the 1986 Presidential Commission on the Space Shuttle Challenger Accident. Dr. Fabian has published articles, reports and papers on aerodynamics, propulsion, space shuttle operations, safety, and international cooperation.

Harold Guy is a medical doctor and associate clinical professor at the University of California School of Medicine. He received his graduate degree in Medicine from Otago University in New Zealand in 1963. After completing his internship, he served as a flight surgeon and medical officer with the Royal New Zealand Air Force in Vietnam. His research interests are in pulmonary function in microgravity, and he has been active in the development of equipment used to perform experiments in space. He was largely responsible for the definition and development of the lung function test system, as co-investigator on the 1991 Space Shuttle Mission, STS-40, Spacelab Life Sciences 1, and its October 1993 follow-on mission, SLS-2.

Mae Jemison is a physician, and former NASA astronaut. She earned her doctorate in medicine from Cornell University in 1981 and after completing her internship joined the Peace Corps as a Medical Officer in Sierra Leone. She joined NASA as a Mission Specialist in 1987 and left the agency in 1993 after completing the "Spacelab-J" Space Shuttle mission, the first joint U.S./Japanese Shuttle mission. On this mission, she conducted life and materials science research and was a co-investigator on the Bone Cell Research experiment. Dr. Jemison has recently founded a company, the Jemison Group, Inc., which researches, develops, and implements advanced technologies, and is currently working on a satellite telecommunication system to improve health care in West Africa.

Nicholas Johnson, Principal Scientist at Kaman Sciences Corporation, is a recognized expert in the space systems of the former Soviet Union and other spacefaring nations. He is also an expert in the evaluation of the potential hazard to spacecraft operations posed by orbital debris. From 1982 to 1991, Mr. Johnson was responsible for the authoritative annual reports, *The Soviet Year in Space*, and he recently authored *The Soviet Reach for the Moon*, which covered programs of the 1960s and 1970s. He has appeared before the U.S. Office of Technology Assessment, the U.S. Congress, and the United Nations as an advisor on orbital debris, and was a member of the NRC Committee on Space Debris, which recently delivered a wide-ranging report on the topic.

Franklin Lemkey is senior consultant scientist at the Materials Technology Laboratory of the United Technologies Research Center. Dr. Lemkey has been with United Technologies since 1960, taking sabbaticals to earn his D. Phil. in Metal Physics at Oxford University in 1974, and to serve as the Director of the NASA Microgravity Science Division for one year (1988-1989). Dr. Lemkey is a former member of the NRC's Space Studies Board and its Committee on Microgravity Research. His work has recently taken him to the former Soviet Union to develop joint technology projects between United Technologies, Ukrainian, and other industrial entities.

Frank Lewis is a Professor of Electrical Engineering (Moncrief -O'Donnell Endowed Chair) at the University of Texas at Arlington (UTA), with special expertise in the areas of robotics and controls. Dr. Lewis is the technical lead of the Advanced Controls Program group within UTA's Automation and Robotics Research Institute which performs research in controls design for non linear robotic and manufacturing systems, and real-time control systems implementation. The group's mission is to help manufacturing companies to implement advanced controls to increase product quality, and improve the flexibility and productivity of production processes. Dr. Lewis earned his Ph.D. from the Georgia Institute of Technology in 1981.

Mary Helen McCay is Professor of Engineering Science and Mechanics at the University of Tennessee Space Institute, in the Center for Laser Applications. Dr. McCay is an expert in materials science and space research in materials processing. She earned her Ph.D. from the University of Florida in 1973 and was a principal investigator in solidification research at NASA's Marshall Space Flight Center from 1975 to 1986. Earlier in her career at Marshall, she developed techniques and apparatuses for crystal growth and other studies that have led to the development of facilities for space laboratories.

Duane McRuer is Chairman of Systems Technology, Inc., an engineering company that has worked with many government agencies including NASA, the Department of Defense, the Federal Aviation Administration, and the Department of Transportation. He is a member of the National Academy of Engineering and was a member of The President's Advisory Committee on the Redesign of the Space Station (1993). In 1989, he chaired an NRC Committee on the Space Station that produced the report, *Space Station Engineering Design Issues*. His interests range from control systems engineering to the dynamics of human operations, and Mr. McRuer has participated in the development of some 50 aerospace vehicles.

Marvin Minsky is a member of the National Academy of Engineering and National Academy of Sciences and is Toshiba Professor of the Media Arts and Sciences at the Massachusetts Institute of Technology. Dr. Minsky's research has led to pioneering theoretical and practical advances in areas including artificial intelligence, neural networks, mechanical robotics, machine perception and industrial automation. In robotics, he designed and constructed some of the first mechanical hands, visual scanners, software and computer interfaces. Dr. Minsky earned his Ph.D. in mathematics from Princeton University in 1954.

W. James Sarjeant is currently Director of the Space Power and Power Conditioning Institute and James Clerk Maxwell Professor of Electrical Engineering at the State University of New York at Buffalo. He earned his Ph.D. from the University of Western Ontario in the field of electric discharge lasers. He has been a member of, or directed, research, design, and development groups within national laboratories and industry in the areas of pulse power components and impulse measurement systems. Dr. Sarjeant has been a member of many NRC, and government-sponsored technical advisory committees working in the field of electrical power.

Laurence Young is a Professor of Aeronautics and Astronautics, and a Professor at the Man-Vehicle Laboratory at MIT. He is a member of the National Academy of Engineering and the Institute of Medicine, and earned his Sc.D. from MIT in 1962. His area of expertise is biomedical engineering, with a special emphasis on space medicine and biology. He was an alternate Payload Specialist for the 1993 Spacelab Life Sciences 2 mission. During that mission, he served as one of the primary crew contacts for science operations at the Payload Operations Control Center at NASA's Marshall Space Flight Center.